ALTERNATING CURRENT

WIRING AND DISTRIBUTION

BY

William Leroy
W. L. R. EMMET.

NEW YORK:
THE ELECTRICAL ENGINEER
1894

Engineering Appropriation

Press of McIlroy & Emmet, 36 Cortlandt St., N. Y.

CONTENTS.

INTRODUCTORY.

The object of this work is to point out the practical significance of some of the laws governing the distribution of alternating currents; also, to explain those laws in such a manner that their nature and relative importance may be realized by practical men without the expenditure of time necessary to the study of complete works on the subject. Tables are given and determinations worked out which show how calculations can be made, and which also serve as illustrations of the principles involved. Mathematical expressions and scientific terms have been avoided as much as possible, since their use would tend to make the work less suggestive to many readers for whom it is intended. In cases where no conventional names exist to express the meanings desired terms have been used which suggest corresponding terms that are generally familiar to persons engaged in electrical work.

To properly study a subject of this kind it is desirable that the mind should form a clear and correct general conception of the fundamental principles before it is burdened with a multiplicity of details. It is hoped that this book may help the reader to form certain ideas and conceptions which tend to make available to him the information obtainable from more thorough and comprehensive works.

ALTERNATING CURRENT

WIRING AND DISTRIBUTION.

1. Influences Affecting Alternating Distribution.—The different effects which influence alternating distribution are very commonly confused with each other by persons who have not carefully studied the subject. It will, therefore, be well to state what these different influences are. We will, therefore, name them in the order in which they are discussed.

Surface or Skin Effect. By this is meant the property possessed by alternating currents of a ttaining a greater density on and near the surface of conductors than in the interior portions, the result of which is that a certain proportion of the conducting metal is practically inoperative. *Inductive Effects,* by which are mean tthe counter E. M. F.'s which are induced in a circuit through the alternations of its own current. *The Inductive Influence of other Alternating Circuits,* which may give rise to periodic or continuous inequalities of distribution. *Capacity Effects,* which are due to the fact that lines and cables may act as electrical condensers, which alternately charge and discharge themselves with the fluctuations of E. M. F. in the circuit.

2. Surface or Skin Effect.—The nature of this phenomenon may be briefly explained as follows :

When a current is started in a wire each line or element of increasing current tends to induce counter E. M. F.'s or reverse currents in the metal in its neighborhood; thus all the metal in the wire is subjected to two opposing forces, one to create current flow and the other to retard it. The central portions of the wire are surrounded by these retarding influences while the outer surface of the wire can receive them from one side only. The result of this is that when a wire is suddenly subjected to an E. M. F. the current begins first to flow on its surface, and an appreciable time elapses before the full current density reaches the centre of the wire. Thus the current may be said to begin on the outside and soak into the wire. If the alternations are sufficiently frequent the central portions of the wire are practically never reached by the current, and the copper available for conducttivity is little greater than what it would be if the conductor were a tube of similar outside diameter. The thickness of the walls of the equivalent tube will be less as the frequency increases. It is easy to understand that this effect is relatively greater with large wires than with small ; also, that it will be much greater with iron than with copper wires.

This surface effect is entirely confined to the wire itself, and has nothing to do with the magnetic field surrounding the wire ; hence it practically amounts to an increase in resistance of the wire, and does not affect the inductance of the cir-

cuit. From the following table it will be seen that with such sizes of wire as are generally desirable in alternating work the reduction of virtual resistance is inappreciable :

TABLE I.

Product of Circular Mils X Cycles per Sec.	Factor.	Product of Circular Mils X Cycles per sec.	Factor.
10,000,000	1.00	70,000,000	1.13
20,000,000	1.01	80,000,000	1.17
30,000,000	1.03	90,000,000	1.20
40,000,000	1.05	100,000,000	1.25
50,000,000	1.08	125,000,000	1.34
60,000,000	1.10	150,000,000	1.43

The factors given in this table multiplied by the resistance to direct currents will give the resistance to alternating currents for copper conductors of circular cross-section.

3 *Counter E. M. F. of Self-Induction.*—With direct currents the only sources of variation of potential outside of the generators or motors are the simple resistances of the lines and other parts of the circuit. These being constant the variations are always proportionate to the currents, and wiring tables can be made which will show accurately the variations that will be met under any set of conditions. With alternating currents the case is different, and in addition to the effects of simple resistances, we have to deal with counter electromotive forces introduced by the inductances of the circuit. These counter E. M. F.'s are caused by the periodic variations in the current which cause changes in the magnetic flux through the circuit. That is, the wires carrying the current are encircled by lines of magnetic force and many of these

lines generally pass through the circuit, so that any change in current strength causes a change in the number of lines which pass through the circuit, and this change generates counter E. M. F. This counter E. M F. is not continuous but periodic, like the current which generates it, and since it is greatest when the magnetic flux is increasing or diminishing most rapidly, its maximum values do not coincide in time with the maximum current values, but come at the instants when the current is changing most rapidly. If the current waves are simply harmonic these instants occur when

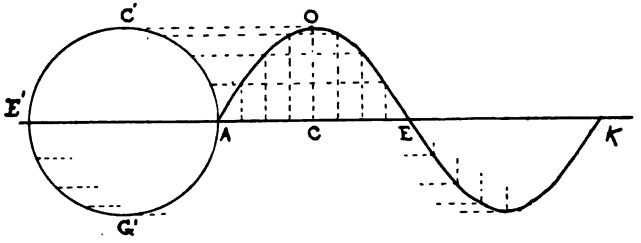


FIG. I.

the current is changing its direction, which is one quarter of a period before and after the current is at its maximum. Thus the current and counter E. M. F. of self-induction differ by a quarter phase.

4. Explanation of Harmonic Variations.—The ideal alternating current should vary according to the laws of simple harmonic quantities, and with good apparatus the variations in fully loaded lines do generally approximate quite closely to these laws. It is, therefore, important that the student

of alternating currents should form a clear conception of the nature of the variations of such quantities. An example of a quantity which varies according to these laws is the distance above or below the floor line of any point on a fly wheel moving at constant speed. The curve in Fig. 1 represents the variation of a harmonic quantity. A K representing the time of its complete period, and the distance of points in the curve from this line represent the values at corresponding instants. The circumference of the circle A C′ E′ G′ is divided in the same manner as the line A K and the corresponding letters and dotted lines show the relation between the circle and the harmonic variable. The distance of the point of the minute hand of a clock above the shelf on which it stands is a harmonic variable whose complete period is one hour. Thus we regard the complete period of such a quantity as 360° or one circumference.

If we had another harmonic curve drawn in Fig. 1, whose period was the same, but whose zero value came at C instead of A, we would say that this curve differed in phase from the curve A O by 90°, or that it lagged 90° behind it, or that it was in quadrature with it.

5. *Energy and Induction.*—If two harmonic quantities of equal periods are in quadrature with each other, that is, differ in phase by 90°, and their simultaneous values are multiplied together, the sum of all the products will be zero, the maximum of each quantity will correspond in time with the zero of the

other, and the products which occur between the maximum and minimum points will be half positive and half negative and will amount in all to zero.

When an alternating current is caused in a circuit by a certain E. M. F., and the phases of this current and E. M. F. are the same, the energy in watts in the circuit is equal to the product of the current in amperes and the E. M. F. in volts, just as is the case of a direct current. If we could have a circuit in which an alternating E. M. F. and the current which it caused were in quadrature with each other, the sum of all the corresponding products of current and E. M. F. would, as stated above, be zero and the energy consumed in the circuit would be nil. This condition is approximately filled when a condenser is connected to a source of alternating E. M. F. A current will exist in the leads to the condenser and an E. M. F. exists at its terminals, but since this current and E. M. F. are practically in quadrature the power in watts of the circuit is very small. If the condenser did not leak or consume energy through the agitation of its dielectric the current and E. M. F. would be in quadrature and the energy zero.

When the current and E. M. F. are of different phase, but not in quadrature, we may regard the E. M. F. as being the resultant of two components, one in phase with the current and one in quadrature with it. From the nature of periodic quantities this division into components is easily effected. If the hypothenuse of a right triangle is made of a length

which will represent in any chosen unit the impressed E. M. F. of a circuit, and if the difference of phase of the E. M. F. and current is shown by the one of the acute angles; then the side opposite to this angle will represent the component of the E. M. F. which is in quadrature with the current, and the side adjacent will represent the component which is in phase with the current. No matter what the nature of the circuit may be or what forms of energy may be developed in it, the total energy of the circuit in watts must equal the product of the current and this component of the E. M. F. which is in phase with the current. This component we therefore call the energy component of the E. M. F. The other component of the E. M. F. can imply the performance of no work, since it is in quadrature with the current. No matter what its origin may be, it is of the nature of a counter E. M. F., and we call it the inductive component of the E. M. F. A clear understanding of this fundamental relation between the work done in a circuit and the phase difference of its E. M. F. and current will do much to elucidate the study of alternating currents.

6. Relation of Current and E. M. F.—In direct current circuits not containing motors the current always equals the E. M. F. divided by the resistance. In alternating circuits this relation seldom exists, for besides being checked by the resistance, the current is opposed by the counter E. M. F. of self-induction which in turn may, or may not, be partly

neutralized by the effect of secondary circuits and other disturbing influences. If the alternating circuit is alone and without iron, its current at a given E. M. F. depends simply on the resultant of two quantities, one is its resistance, and the other, for want of a better name, may be called its *inductive resistance*. This inductive resistance is equal to the counter E. M. F. of self-induction divided by the current.

The resultant of these two quantities is called the *impedance*. Thus in an alternating circuit the current is equal to the impressed E. M. F. divided by the impedance, just as in a direct current circuit the current equals the E. M. F. divided by the resistance. In circuits which are so arranged that their energy may be absorbed in other ways than by the overcoming of their own resistance, the explanation of impedance must be made broader, and instead of being the resultant of a resistance and a counter E. M. F. of self-induction, we may say that it is the resultant of an energy component and an inductive component; the former being made up of the resistance and other causes of energy consumption to which it is subject; and the latter being due to the combined effect of the induction of its own current and that of other currents to which it has given rise in secondaries, iron cores, etc. We will coin a name for this energy component of the impedance and call it the *energy resistance* just as we have called the inductive component the *inductive resistance*. If overhead lines are considered alone the components of impedance

consist in simple resistance and self-induction, while if transformers are used other influences are introduced.

The counter E. M. F. of induction, and consequently the impedance, varies with the frequency of alternations and with the form and nature of the circuit. High frequencies imply rapid current changes, and consequently large inductive effects; these effects being due to the rapidity of change in magnetic flux. It is also easily seen that in a circuit consisting of an outgoing and return wire laid side by side there is little room for magnetic flux through the circuit, and consequently there is little induction; while if the wires are separated the induction is increased. If the wire is wound into a coil the induction is multiplied, and if iron is inserted in the coil the magnetic flux through the circuit is enormously increased. The impedances of isolated circuits without iron, like overhead lines, are the same for all current strengths, while in circuits with iron they will vary more or less with the varying losses and degrees of magnetization of the iron for different current strengths. We cannot correctly estimate the drop introduced by a line from the line impedance alone, since it may not correspond in phase with the total impedance of the circuit which is the quantity which determines the current flow for any given E. M. F. applied.

7. Electromotive Forces —If the curve in Fig. 1 shows the variations of an alternate current whose

complete period is represented by A K, and whose maximum value is represented by the line O C, we see that the instants when this current is changing its strength most rapidly occur at A, E and K; hence, as has been explained above, the maximum changes of magnetic flux, and consequently the maximum counter E. M. F.'s occur at these points, which are removed by 90° from the maximum values of the current.

To create a current in an alternating circuit having inductance, and in which no work is done save that of overcoming resistance, sufficient E. M. F. must be generated to do this work, and in addition a sufficient amount to overcome the counter E. M. F. Thus the energy in watts in the circuit may be much less than the product of the volts at the terminals and the amperes. In any alternating circuit having inductance the E. M. F. supplied may be considered as made up of two components, one only of which is effective in doing work, the other simply overcoming the counter E. M. F. The watts of energy in the circuit being the product of the effective E. M. F. in volts and the current in amperes. These two parts we have called the energy component and the inductance component of the E. M. F.; they are both periodic quantities and differ in phase by 90°, as explained. The impressed E. M. F., which is necessary to cause the current in the circuit, is also a periodic quantity, and its phase is somewhere between those of its components, and naturally nearer to that of the greater of the two.

8. Diagramatic Representation.—It will be well to state here a law of harmonic quantities which, however, need not be demonstrated. When two harmonic quantities of the same period but different phase are added together they will form a third harmonic quantity of the same period, as shown in Fig. 2 in which C P + B P = A P and P′ C′ — P′ B′ = P′ A′, etc.

If the length of the line A B, Fig. 3, represent the maximum value of one harmonic quantity, and the length of the line A C represent another of the

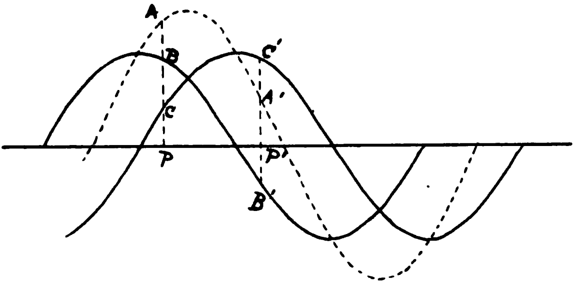


FIG. 2.

same period, and if the angle B A C represent their difference of phase, then the line A D, the diagonal of the parallelogram constructed on A B and A C, will represent in length the maximum of the resultant harmonic quantity, and the angles that this line makes with A B and A C will be the angles by which its phase differs from the quantities which these lines represent. With the two quantities we are considering, viz., the counter E. M. F. of induc·duction and the effective E. M. F., the phase differ-

ence is 90°, or a right angle; the parallelogram, therefore, in this case becomes a rectangle with these two quantities as sides adjacent to the right angle. The diagonal represents the impressed E. M. F. in length and in phase; or, since the two diagonals of a rectangle are equal we may simply construct a triangle, Fig. 4, in which the hypothenuse represents the impressed E. M. F. The angle at A is the angle by which the current lags behind the impressed E. M. F., and is called the *lag angle* of the circuit.

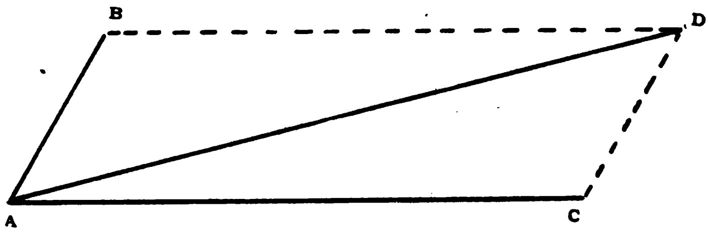
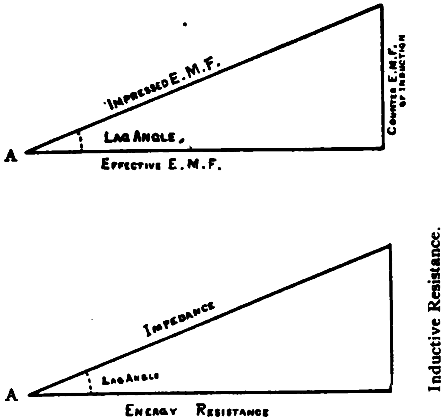


FIG. 3.

In the same way we may construct a triangle, Fig. 5, showing the components of impedance, namely the energy resistance and the inductive resistance. Both these quantities are expressed in ohms, and if they are each multiplied by the current in amperes the products will be the quantities represented by the sides of the triangle in Fig. 4 expressed in volts.

Suppose we have a circuit consisting of three parts, each with a different lag angle, the impressed

E. M. F. required in each part being respectively represented in quantity and phase by the lines A B, B C,



FIGS. 4 AND 5.

and C D, Fig. 6, the energy components being represented by the horizontal lines and the induction components of the E. M. F. by the vertical lines.

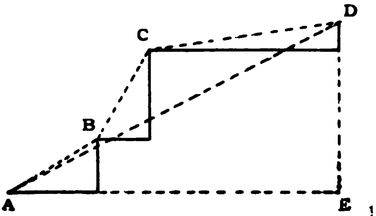


FIG. 6.

Then the line A D is the impressed E. M. F. required in the whole circuit, A E is the energy component of

this E. M. F., and D E its induction component. Thus the total energy component of the E. M. F. of the circuit is equal to the sum of all the energy components of its parts; also the sum of all the induction components is equal to the induction component of the circuit. The sum of the impressed E. M. F.'s of the parts is greater than the impressed E. M. F. of the whole, since the parts are of different phases. In the same way, if we sum all the energy resistances in a circuit, and also all

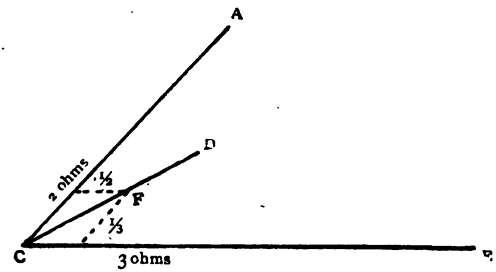


FIG. 7.

the inductive resistances, the resultant of these two sums will be the impedance of the circuit, and the sum of all the impedances in the circuit will be greater than the total impedance unless the impedances of all the parts have the same phase, in which case all the parts have the same lag angle. If we want to find the impedance equivalent to two known impedances in parallel, we must proceed as follows: From the reciprocals of

the two impedances, each with its proper phase, construct a parallelogram. The direction of the diagonal will give the phase of the resultant impedance and the reciprocal of its length will give its amount. Suppose we have two impedances of 2 ohms and 3 ohms in parallel. These may be represented in length and in phase by the lines A C and C F, Fig. 7. The reciprocals of 2 and 3 are ½ and ⅓. Constructing a parallelogram, as

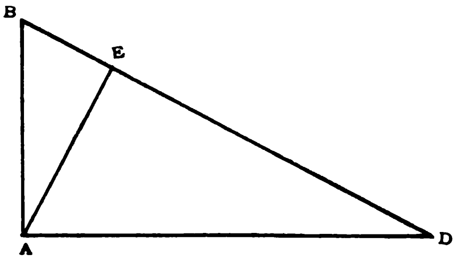


FIG. 8.

shown, and laying off C D, equal to $\frac{1}{\text{C F}}$, the line C D represents in amount and phase, the resultant impedance, and by measurement we find it to be about *1.3* ohms. These angles and results can also be obtained by calculation, but the graphic method is more suggestive and practically as easy of application. Where two impedances are in quadrature with each other their resultant in parallel may be found as follows: Construct a right triangle whose sides adjacent to the right angle

represent in length and direction the two impedances in question. The perpendicular from the right angle to the hypothenuse will represent the resultant impedance in length and direction. In Fig. 8, if A B and A D represent two impedances in quadrature, then A E will represent the resultant of the two in parallel.

9. Nature of Circuits of Different Classes.—In order that a circuit may have inductance it must be so arranged that current in it causes the passage of lines of magnetic force through it. A circuit of incandescent lamps is an example of a non-inductive circuit. It can embrace only a small number of lines of force in proportion to the energy it consumes and consequently may be considered as having no inductance, although, of course, it has a little; the current in it is practically in phase with the impressed E. M. F. A circuit consisting of a single loop of very large wire, with its sides well separated may have a very large lag angle, since it will embrace a considerable number of lines of force, but will consume very little energy, owing to its low resistance. No matter what form of energy is consumed in a circuit its effect on the lag angle is the same, whether it is expended in overcoming resistance, and thus heating the circuit itself, or or whether it is delivered to a secondary circuit, or is consumed in eddy currents, or in hysteresis in an iron core, its effect is always to bring the impressed E. M. F. more nearly into phase with the current that is to decrease the lag angle. Thus a circuit

may have a very large counter E. M. F. of self induction, but such a small current, that a slight energy loss makes the lag angle quite small. For example, the primary circuit of an ordinary transformer, with secondary circuit open, has an energy component of about 70 per cent. of the impressed E. M. F., corresponding to a lag angle of about 45°, while the same coil, if wound on an open instead of a closed iron magnetic circuit might have a lag angle of 80°, because in that case a larger current would be necessary to create the same conditions in the iron. This increased current would increase the induction component in direct ratio, but would only slightly increase the energy component, since only a small proportion of the lost energy is introduced by the resistance of the wire, the greater part of it being expended in hysteresis and eddy currents.

10. Other Influences.—If a condenser is connected between the leads of an alternating circuit it alternately receives and discharges current as the E. M. F. at its terminals changes, being charged as the potential rises and discharging into the circuit as the potential falls. Thus it returns E. M. F. to the line just at the time when the E. M. F. of the line is being opposed by the counter E. M. F. of self-induction if any exists. Thus inductance and capacity tend to neutralize each other, capacity tending to decrease the lag angle, and often causing a negative lag angle, in which case the drop of potential in the circuit may be less than that which

would be due to the energy loss alone. The two leads of every circuit form a condenser of a certain capacity, but the effect of that capacity in overhead lines is unimportant except in lines of great length with very high potential.

The lag angles in the circuit of alternating motors vary largely with the size and design of the motors, and with their condition of load. The energy component in the circuit of a non-synchronous motor of ordinary design will range from 85 to 95 per cent. at full load and as low as 50 per cent. on light load; large motors with small air gap have relatively large energy factors. Synchronous motors when lightly loaded and working with strongly excited fields will take energy from the line as the impressed E. M. F. wave rises and return it as it falls, thus acting like condensers tending to reduce the lag angle or to make it negative. Thus, where several such motors are run in parallel, those which are lightly loaded may, in a measure, share the load of the others by raising the potential, and thus compensating for the drop which the loaded motors would otherwise introduce. By controlling the field strength of such a lightly loaded synchronous motor it can be made to regulate the pressure on the line to which it is connected, by compensating for the effects of inductances in the circuit.

11. Effect of Transformers.—Well designed transformers of the ordinary kind when fully loaded with an absolutely non-inductive load, will have a

lag angle at their primary terminals of about 4°; that is, the E. M. F. at the primary terminals has an energy component of 99.8 per cent. and an inductive component of 6 per cent. In large transformers the energy component is still greater, and in smaller sizes it is generally less. At half load, the energy component is less, but still about 99.5 per cent., which corresponds to an inductive component of 10 per cent. We have already stated that at no load the current in the primary of a transformer has an energy component of about 70 per cent.

The ordinary load of an alternator running incandescent lights includes the lamps, the secondary wiring, the transformers, and the primary mains. When the feeders are at full load the transformers will, on the average, be possibly at one-half to three-quarters load. A certain amount of inductance is introduced by the large wires in the secondary circuits, also by the primary feeders, and the whole may be estimated as having an energy component of 99 per cent., which may be differently stated by saying that the current in the circuit has an energy factor or power factor of .99 which corresponds to an induction factor of .14, and a lag angle of 8°; .99 and .14 being the two sides of a right triangle whose hypothenuse is 1, and whose smaller angle is 8°. Table II. gives power and induction factors corresponding to different lag angles.

TABLE II.

Lag Angle.	Power Factor.	Induction Factor.		Lag Angle.	Power Factor.	Induction Factor.	
Degrees.			Degrees.	Degrees.			Degrees.
1	.9998	.0174	89	23	.9205	.3907	67
2	.9994	.0349	88	24	.9135	.4067	66
3	.9986	.0523	87	25	.9063	.4226	65
4	.9976	.0698	86	26	.8988	.4384	64
5	.9962	.0872	85	27	.8910	.4540	63
6	.9945	.1045	84	28	.8829	.4695	62
7	.9925	.1219	83	29	.8746	.4848	61
8	.9903	.1392	82	30	.8660	.5000	60
9	.9877	.1564	81	31	.8572	.5150	59
10	.9848	.1736	80	32	.8480	.5299	58
11	.9816	.1908	79	33	.8387	.5446	57
12	.9781	.2079	78	34	.8290	.5592	56
13	.9744	.2249	77	35	.8191	.5736	55
14	.9703	.2419	76	36	.8090	.5878	54
15	.9659	.2588	75	37	.7986	.6018	53
16	.9613	.2756	74	38	.7880	.6156	52
17	.9563	.2924	73	39	.7771	.6293	51
18	.9511	.3090	72	40	.7660	.6428	50
19	.9455	.3256	71	41	.7547	.6561	49
20	.9397	.3420	70	42	.7431	.6691	48
21	.9336	.3584	69	43	.7313	.6820	47
22	.9272	.3746	68	44	.7193	.6946	46
				45	.7071	.7071	45
	Induction Factor.	Power Factor.	Lag Angle.		Induction Factor.	Power Factor.	Lag Angle.

12. Inductive Resistance of Lines.—When an alternating current flows in the outgoing and return wires of a circuit there is a periodically changing magnetic flux through the circuit which induces a periodic counter E. M. F. If the wires are brought close together this is naturally reduced; if they are separated it is increased, since more lines of force are surrounded by the circuit. For a given current and distance between centres, the counter E. M. F. is somewhat greater if the wires are small than when they are large, owing to magnetic flux

through the copper of the wires themselves. The resistance of large wires is, however, less; consequently the proportion of inductive resistance to resistance is much greater in large wires. We have seen (see Fig. 5) that the resultant of the resistance and inductive resistance is the impedance. Table III., gives resistances, inductive resistances and impedances per mile of copper wire circuits of different sizes and at different distances between centres, and for frequencies of 60 and 125 ~ per second. This table is figured on the assumption that the current waves are simply harmonic. In practice, it will be well to add about 15 per cent. to the inductive resistances given in the table as an allowance for variations in the current waves.

The curves on page 29 correspond to the inductive resistances given in the table, and show their amounts for greater and smaller distances between centres.

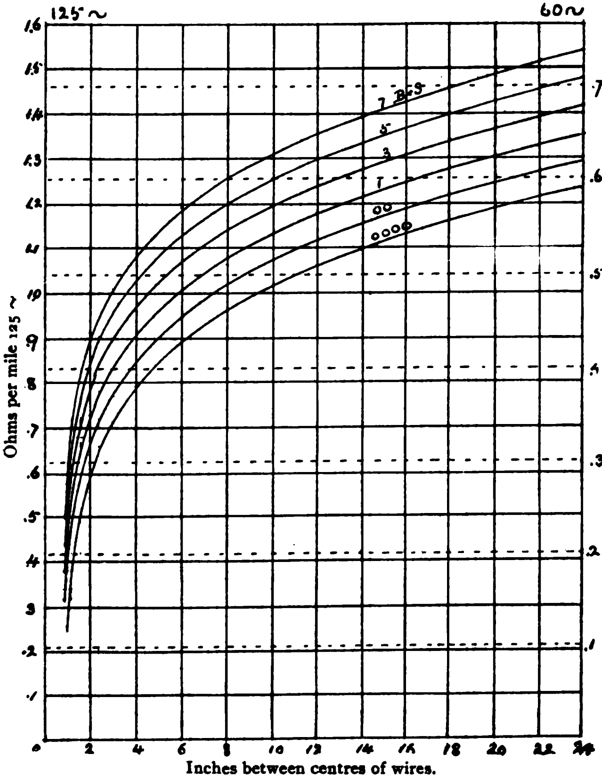
From what has been said of the properties of circuits of different kinds, it will be seen that in a large proportion of the practical cases where we may want to make line determinations, we will be dealing with circuits which have power factors exceeding .95 ; though in circuits having a large proportion of their load in motors or circuits with very large and highly inductive line losses, the power factors may be much less.

In lighting work the loss is usually made small on account of regulation, and the lamps being non-inductive, the power factors are usually as high as .98 or more. If we assume a certain power factor

TABLE III.

Gauge No. B.and S. Wire.	Resistance in Ohms per Mile.	Inductive Resistance and Impedance in Ohms per Mile at 60 ~ per Second.						Inductive Resistance and Impedance in Ohms per Mile at 125 ~ per Second.					
		12 Inches Between Centres.		18 Inches Between Centres.		24 Inches Between Centres.		12 Inches Between Centres.		18 Inches Between Centres.		24 Inches Between Centres.	
		Ind. R.	Imp.	Ind. R.	Imp.	Ind. R.	Imp.	Ind. R.	Imp.	Ind. R.	Imp.	Ind. R.	Imp.
0000	.259	.508	.570	.557	.615	.591	.646	1.06	1.092	1.17	1.190	1.23	1.260
000	.324	.523	.616	.573	.658	.607	.686	1.09	1.138	1.20	1.237	1.26	1.305
00	.412	.534	.682	.588	.725	.618	.749	1.12	1.194	1.23	1.297	1.29	1.357
0	.519	.550	.756	.603	.796	.633	.818	1.15	1.258	1.26	1.360	1.32	1.415
1	.655	.565	.865	.614	.896	.648	.920	1.18	1.349	1.28	1.436	1.35	1.50
2	.826	.580	1.008	.629	1.038	.663	1.06	1.21	1.466	1.31	1.55	1.38	1.61
3	1.041	.591	1.196	.644	1.223	.674	1.24	1.24	1.61	1.34	1.70	1.41	1.75
4	1.313	.606	1.448	.656	1.467	.690	1.48	1.26	1.82	1.37	1.89	1.44	1.94
5	1.656	.620	1.76	.670	1.78	.704	1.80	1.30	2.10	1.40	2.17	1.47	2.22
6	2.088	.633	2.18	.685	2.20	.720	2.21	1.32	2.46	1.43	2.51	1.49	2.56
7	2.633	.647	2.71	.700	2.72	.730	2.73	1.35	2.93	1.46	3.00	1.52	3.04
8	3.320	662	3.38	.712	3.39	.742	3.40	1.38	3.59	1.48	3.63	1.55	3.66
9	4.186	.677	4.21	.727	4.22	.761	4.23	1.41	4.39	1.51	4.43	1.58	4.45
10	5.280	.688	5.32	.742	5.33	.776	5.34	1.44	5.47	1.54	5.50	1.62	5.53

in the whole circuit, which, of course, corresponds to a certain lag angle, we can make a table of



equivalent resistances from which we can calculate line losses directly, as from an ordinary resistance

TABLE IV.

EQUIVALENT RESISTANCES.

Figured on assumption that circuit has a power factor of .96.

Gauge No. B and S.	Ohms per Mile of Wire.	
	60 ~ per sec.	125 ~ per sec.
0000	.42	.62
000	.49	.68
00	.58	.77
0	.68	.89
1	.82	1.02
2	.98	1.19
3	1.17	1.38
4	1.46	1.68
5	1.80	2.02
6	2.21	2.44
7	2.75	2.98
8	3.37	3.61
9	4.04	4.49
10	5.31	5.56

table with direct currents. Table IV is calculated on the assumption that the total power factor of the circuit calculated is .96 and that the current waves are somewhat distorted from the true sine curve. The equivalent resistances given in the table are the approximate amounts by which the total impedance of the circuit would be increased by a mile of the wire in question. This table, though only an approximation, is sufficiently accurate for use in most cases. When the power factor is more than .96, as is generally the case where much of the load is incandescent lamps, the figures given are high and therefore on the safe side. Where line losses are large and load inductive, more accurate methods must be used.

13. Relations of Quantities.—The following rules applicable to overhead lines, will be understood from a study of Figs. 4 and 5 with the explanations that accompany them.

1. The impedance is equal to the square root of the sum of the squares of the resistance and inductive resistance.

2. The induction component of volts lost in line equals the inductive resistance in ohms multiplied by the current in amperes.

3. The energy component of volts lost in line is equal to the resistance in ohms multiplied by the current in amperes.

Where the circuit is in the presence of iron or of a secondary circuit, other energy is consumed beside that necessary to overcome resistance, hence Rule 1 must be modified by the substitution of the word *energy-resistance*, or some equivalent, for the word *resistance*.

The following are of universal application:

4. The energy component of the E. M. F. in volts is equal to the energy expended in the circuit in watts divided by the current in amperes.

5. The energy resistance in ohms is equal to the energy in watts divided by the mean square of the current in amperes.

6. The potential difference between the ends of a circuit, *i.e.*, the impressed E. M. F. in volts, is equal to the square root of the sum of the squares of the energy and induction components of the E. M. F., both expressed in volts.

Rule 6 might also be expressed thus:

The impressed E. M. F. equals the square root of the sum of the squares of the effective E. M. F. and the counter E. M. F. of induction.

These rules are founded upon the fact that the square of the hypothenuse of a right triangle is equal to the sum of the squares of the other two sides.

14. Practical Determinations by Diagrams.—We have already shown how the E. M. F.'s in any alternating circuit having inductance may be represented by a triangle, Fig. 4, or a succession of triangles, Fig. 6, which may be combined to form a resultant triangle. We will now take a practical case and show how a chart may be constructed which will show the distribution of E. M. F. on the circuit, and the proportion of energy consumed in its different parts. The processes of making determinations are rendered less confusing if we reduce all potentials to the same basis, that is, if we divide the current in the secondaries of transformers by the ratio of transformation, and figure as if all transformers had a ratio of transformation of unity.

We will assume a case where 500 incandescent lamps of 57.5 watts each are distributed on secondaries connected to transformers of different sizes and on the average about half loaded. These transformers are connected by a pair of No. 2 B. and S. wires to the generator which is 2 miles distant, the wires are 18″ apart, and the frequency of the generator is 125 ~ per second, that is, 15,000 alter-

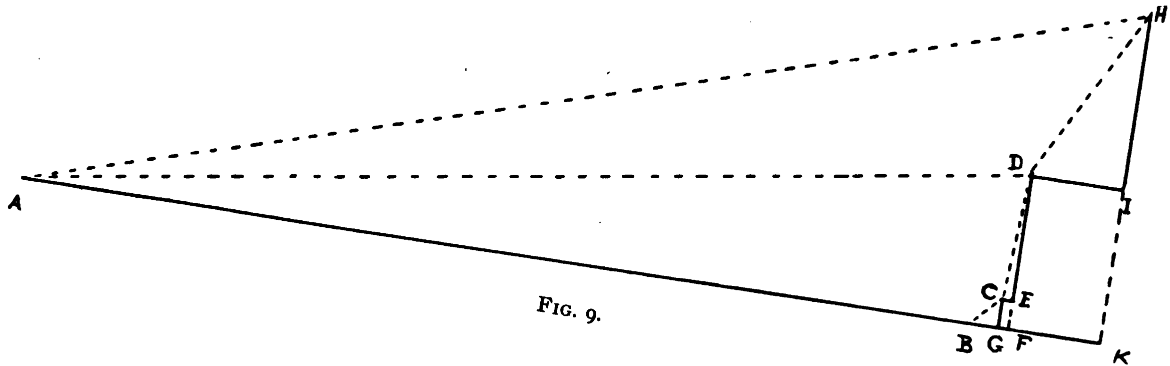


FIG. 9.

nations per second. The voltage at the lamps is 100 and the ratio of transformation 10.

In Fig. 9 the horizontal lines represent energy components of E. M. F., and the vertical lines inductive components of E. M. F., the figure being constructed on such a scale that one-half inch represents 100 volts. Since the lamps themselves are practically non-inductive (see Sec. 9) we may represent the E. M. F. at their terminals by a horizontal line, five inches long, A B. The next element to be considered is the secondary wiring. Large wires are used in this, which give a considerable amount of inductance in proportion to their resistance. The wiring is done for an energy loss of 3 per cent., therefore, we lay off B G = 30 volts and assume an inductance component G C of the same amount. Now we come to the losses introduced by the transformers. First, there is the loss due to the resistance of the coils, which we may call 1 per cent. Second, there is the inductance loss, or counter E. M. F. in quadrature with the current introduced by the transformer. In fully loaded transformers, this would not exceed 6 per cent., but in the present case we may regard it as about 12.5 per cent. Third ,we have the loss in iron cores of transformers. This loss is similar in its effects to the addition of another secondary; it being, in fact, largely caused by secondary or eddy currents in the iron. Its effect, then, is practically to make necessary a greater current in the primary circuit, and it should be so applied. With fully loaded large transformers this loss should be about

3 per cent. In the present case it will be as high as 5 per cent., and we have so taken it. We, therefore, lay off C E = 10 volts to represent the resistance loss, and E D = 130 volts to represent the inductance loss in the transformers. Next comes the line. If there were no loss in transformers the current here would be 28.75 amperes; to this we must add the 5 per cent. for core loss which makes the line current 30.19. From Table III., p. 28, we see that the resistance of the 4 miles of No. 2 wire is 3.3 ohms, and that the inductive resistance will, in this case, be 1.32 × 4 = 5.24 ohms. To this we must add 15 per cent. for distortion of current waves, making it 6.04 ohms. The current, 30.19 (amperes), multiplied by 3.3 (ohms) gives a resistance drop of 99 volts, and the same current multiplied by 6.04, the inductive resistance, gives 182 volts inductance drop. Therefore we lay off D I = 99 volts and I H = 182 volts. Now if we connect A and H the line A H will represent the E. M. F. required at the generator terminals, and it will be found to be 1,188 volts. If we extend H I to K, A K will represent the energy component, 1,139 volts; therefore, the actual power in the circuit in watts is 1,139 × 3,019 = 34,300, while the volt-amperes at the generator terminals will be 35,800. Therefore, a 36 K. W. dynamo will be required, though the power needed to drive it, if its efficiency is 90 per cent., will only be 38 K. W. or 51 mechanical H. P. The generator will have to be over-compounded about 19 per cent. to be self-regulating. If there were no line inductance the E. M. F.

required at the generator would be represented by the distance from A to I which is $5\frac{3}{4}'' = 1,150$ volts. The line B H, which by measurement is found to equal 201 volts, is the impressed E. M. F. on line. If we had figured that the loss in volts in circuit were equal to the line impedance multiplied by the current, as is sometimes incorrectly done, we would have anticipated a drop of 201 volts in line alone, while the total loss, including secondary and transformer is only 188, the portion due to the line being about 150 volts. If the line loss were smaller, the difference between the volts drop in line and the real loss would be relatively greater. The above case is assumed for illustration, the loss is greater than is ordinarily allowed in practical lines.

15. Arithmetical Determination.—The same results which we have arrived at diagramatically we may obtain by arithmetic, as follows:

	Energy Component in Volts.	Inductance Component in Volts.	Current in Amperes.
Lamps reduced to basis of 1,000 volts..........	1,000	....	28.75
Secondary wiring 3 % resistance and 3 % inductance loss......	30	30	
	1,030	30	
Transformers			
Resistance loss about 1% = ..	10		
Inductance loss about 12.5 % of the volts at secondary terminals = ...	....	130	
	1,040	160	

Brought forward,	1,040	160	28.75
Primary current increase by core loss at this state of load 5 % = ...	....	....	1.44
Line.			——
Current in line..............			30.19
Resistance loss 3.3 × 30.19 ..	99		
Inductance loss 5.24 + 15% = 6.04; 6.04 × 30.19 = ...	....	182	
	1,139	342	

Taking the square root of the sum of the squares of 1,139 and 342, we find it to be 1,188 which is the E. M. F. in volts required at the generator terminals, and is the same as that obtained by measurement of the line A H in the figure.

The triangle A D F, Fig. 7 represents the portion of the system beyond the primary terminals of the transformer. It is ordinarily not necessary to construct this triangle from its components, as we have done since we may estimate its proportions in most cases. In a circuit exclusively of incandescent lamps with a lot of transformers of modern design and different sizes, on the average about half loaded, like that considered here, the inductance factor is about 17 per cent., corresponding to an energy factor of 98 per cent.

If the transformers were of old design the energy factor might be 95 per cent. or less.

If the transformers were of good design and fully loaded, the energy factor might be over 99.5 per cent.

Where motors or other inductive load exists, the energy factor will have to be computed or esti-

mated from the information which has been given as to energy factors of motors. A circuit of transformers with inductive motors for their load would, under average conditions, have an energy factor of 80 per cent. or less, though fully loaded motors with fully loaded transformers might have an energy factor of 90 per cent. or more.

16. Step-Up and Step-Down Transformer.—The fact that very high electrical pressures are unsafe and inconvenient, both in generators and distributing circuits, makes the use of these transformers necessary where power is to be transmitted long distances. There is no difficulty in building transformers which will stand very high pressures and will transform them in any desired ratio. Since the efficiency of transformation is no less at high pressures than at low, we see that practically the only limit to the distance to which energy can be economically transmitted is the limit of potential difference to which transformers can be adapted and for which lines can be insulated.

It must always be borne in mind that with periodic currents the pressure shown by the voltmeter is the square root of the mean square of the potential differences, and that the maximum strain to which insulation is subjected is equal, with simple periodic currents, to this voltmeter reading multiplied by 1.414. We cannot say just what the practical limits of dynamo and transformer pressures are, but present practice seems to indicate that 5,000 volts mean as about as high as is ever

desirable in a dynamo, while lines and transformers have been successfully worked with pressures of 20,000 and 30,000 volts.

In making the wiring determinations for any installation we naturally must assume the conditions which will exist at maximum load when the loss is greatest. We have already said that the transformers on distributing lines at times of maximum load are not, on the average fully loaded, which fact increases the lag angle of the circuit and reduces its power factor. With step-up and step-down transformers the case is different, since they can be proportioned so that they are fully loaded at times of maximum load. These transformers are generally of large size and modern design; consequently the losses they introduce are relatively small, as the assumptions made in the following determination will indicate.

17. Determinations, Step-Up and Step-Down Transformers.—For illustration of this subject, we will assume a practical case where a water power is situated 14 miles from a town where it is desired to run 500 K. W. in incandescent lights in a compact district, current being distributed on a three-wire low tension underground system, fed from a transformer station. The pressure at the station is 130 volts at full load, and at the lamps 120 volts. The power delivered at transformer station must, therefore, be $\frac{500}{120} \times 130 = 541$ K. W. We want to use a maximum potential of about 10,000 volts, and have

available transformers of 40 K. W. capacity. At the receiving station we decided to use seven pairs of these having ratios of transformation of 10 to 1, with their primaries in two series, and their secondaries connected on the three-wire system. For convenience we reduce the secondary circuit to line potential and find that it corresponds to 9,100 volts and 59.7 amperes. For our line we will figure on No. 00 B. and S. wire. The frequency used is 60 ~. For the distributing circuits and lights we will assume an energy factor of ..99, corresponding to an induction factor of .14. The line has a resistance per mile of .412 ohm, and from the table an inductive resistance of .534, the wires being 12 inches apart. To this figure we add 15 per cent. for wave distortion, making it .614 ohm.

We may then proceed with the determination, as follows:

	Energy Component. Volts.	Induction Component. Volts.	Current. Amperes.
Secondary circuits:			
Power 99% of 9,100	9,000		
Induction 14% of 9,100........	....	1,270	
Current.....................	...	...	59.7
Step-Down Transformers.			
Resistance loss, 1% of 9,100..	91		
Induction loss, 6% of 9,100...	....	546	
Core loss, 3% of 59.7	....	....	1.78
			61.5
Line, 28 *miles of wire.*			
Resistance loss, .412×28×61.5	710		
Induction loss, .614×28×61.5.	....	1,060	
	9,801	2,876	

Brought forward,	9,801	2,876	61.5
At Secondary of Step Up Transf.			
$\sqrt{9,801^2+2,876^2}=10,200$ volts			
Step Up Transformers.			
Resistance loss, 1% of 10,200..	102		
Induction loss, 6% of 10,200...	....	612	
Core loss, 3% of 61.5.....	....	....	1.85
	9,903	3,488	63.4
$\sqrt{9,903^2 + 3,488^2}$ = ...	10,500		

Thus we see that the generator must deliver 665 kilovolt amperes and 630 kilowatts. The efficiency of transmission from generator terminals to secondary terminals of step-down transformers is 86 per cent. Sixteen of the same 40 K. W. transformers connected in two series to line, and in two series to generator will just fill the requirements for step-up transformers. The pressure at the generator terminals will be 1,050 volts. The generator capacity required is 665 K. W. Assuming a generator efficiency of 92 per cent. the power required will be 685 mechanical K. W. or 920 H. P. The total efficiency from water wheel to lamps will be 73 per cent.

In this determination the transformers are large and fully loaded; therefore, the allowances for their losses are smaller than in the other case considered. Fig. 10 is a diagram of this circuit on a scale of one-half inch = 1,000 volts.

18. Interference of Circuits.—When two alternating circuits are near together it may happen that some of the periodically fluctuating circles of magnetic force which surround the wires of one circuit

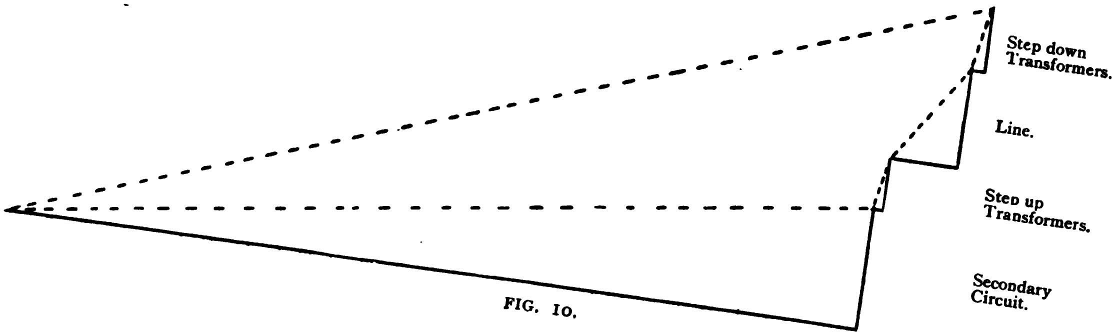

Step down
Transformers.
Line.
Step up
Transformers.
Secondary
Circuit.

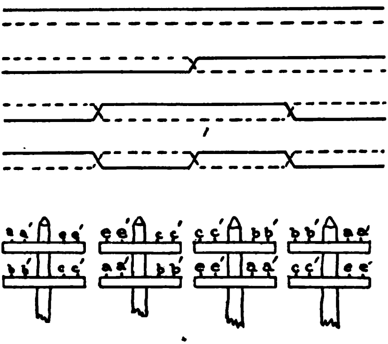
FIG. 10.

may link themselves through the other circuit. If this linkage is not compensated for by the fact that other lines of force are at the same time linked in the opposite direction, the result will be that one circuit will act as a secondary to the other and receive impulses of E. M. F. from it. If the periods of the circuits are the same, this mutual induction will simply tend to increase the drop in one circuit and decrease it in the other. If, however, the periods of the circuits are different there will be a periodic rise and fall of potential in both circuits, the maximum of which will come at the instants when the two current waves come into step. In either of these cases distribution may be seriously impaired, undue pressure being occasioned in one case and visible fluctuations of light in the other.

The troubles occasioned by this interference of circuits are easily overcome by so arranging the relative positions of wires, that one part of a circuit exactly counteracts the effects produced by the other. Fig. 11 shows four circuits, none of which could have any effect on any of the others, no matter what their relative positions, provided their crossings and ends had the relative positions shown.

Fig. 12 shows an arrangement of four circuits on a single pole line, which will entirely avoid mutual induction. The two wires of each circuit are indicated by the letters *a* and *a'*, *b* and *b'*, etc. They should occupy the relative positions shown in each of the figures for a distance of one-quarter of the whole distance they are in company.

The same plan of arrangement can be used with any number of circuits. If the distance between two circuits is great in comparison with the distance between wires of each circuit, the interference will be small, whether crossings are made or not. Thus, for this reason, as well as for the reduction of self-induction, it is desirable to place the outgoing and return wires of an alternating circuit as close together as possible, unless the



FIGS. 11. AND 12.

lines are so long, and the potential so high, that the static capacity becomes of importance.

19. Multiphase Systems.—Such a system consists essentially of the use of two or more alternating currents of equal period but differing in phase. The advantage of these systems is that they make possible the use of the class of motors known as the rotating field type which work without mov-

able contacts, and possess many excellent qualities which have not yet been attained with single phase motors. To have any clear understanding of the principles or action of multiphase currents it is necessary to understand the laws governing the combination of periodic quantities, the nature of which has been hinted at in the preceding pages. These laws are very simple and are clearly explained in many books on electricity and alternating currents. From the method of construction of the periodic curve given in Section 4, it is not difficult to draw curves of different phases, and, by adding

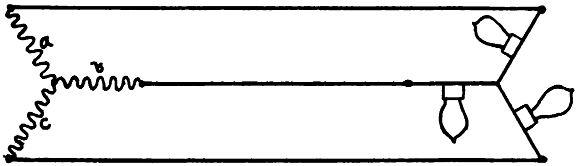


FIG. 13.

their vertical ordinates, to see how they combine to form other periodic curves and what the maximum and phases of the new curves will be with relation to their component curves.

At present we will simply state some of the facts that have practical bearing on the question of distribution.

20. Three Phase System.—In this system several different sets of connections may be used; the relation of currents in lines, however, are the same in all cases. Fig. 13 will serve to illustrate the system as far as distribution is concerned.

In the generator there are three sets of coils *a*, *b* and *c*, which are connected to the lines and together, as shown, and in which are generated periodic E. M. F.'s which differ from each other in phase by 120°. These E. M. F.'s can be illustrated in phase and quantity by the lines *a o*, *b o* and *c o*, Fig. 14, these potentials being all equal. If the potential difference between the centre and each of the coil ends is 1, the potential difference be-

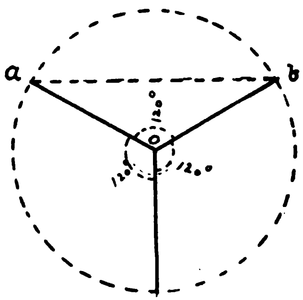


FIG. 14.

tween two of the coil ends is $\sqrt{3} = 1.732$, and is represented by the line *a b*, which is the resultant of the combination of *o a* and *o b*. We see from the figure that the load on the three conductors may be connected either between the wires or from the wires to a common centre. If the pressure between wires is 1, the pressure from any wire to the common centre is $\frac{1}{1.732} = .577$.

When two equal periodic quantities differing in

phase by 120° are combined, their resultant is another periodic quantity equal to each of its components. Thus, in the circuit represented by Fig. 13, each wire may be said to act as a return for the other two, and in so doing receives only its proper share of the load. The different branches may therefore be regarded as equivalent to three separate circuits each supplying one lamp, and using a ground return in which there is no loss. Suppose the pressure for each of these lamps was 100 volts, then the pressure between the ends of two of the wires will be $173.2 = \sqrt{3} \times 100$ volts. Suppose we compare this circuit with a two-wire single phase circuit having the same pressure between wires, hence the same strain on insulation, and transmitting the same energy. In one case we have three circuits not needing return wires, working on 100 volts, and in the other case a circuit working at 173.2 volts, but requiring a return conductor.

Suppose the current in each of the lamps in the three-phase case is one ampere, then in the single phase two-wire case the current must be $\frac{3}{\sqrt{3}} = \sqrt{3}$, or in the two wires $2\sqrt{3}$, the energy transmitted being the same in both cases. Thus, in the three phase line we have to carry three amperes the single length of the line, while in the two-wire line we have to carry $\sqrt{3}$ amperes twice the length of the line. The energy loss in a line is equal to the resistance multiplied by the square of the current, and consequently the cop-

per required for a given loss of energy is proportional to the square of the current; hence in this case the amounts of copper required are in the proportion of $(2\sqrt{3})^2$ and 3^2 which is 4 to 3. So we see that with the same strain on insulation, and same power transmitted and lost, the three phase system requires 25 per cent. less copper than the single phase alternating current system.

21. Three Phase Determinations.—In a three phase circuit each wire is affected, practically, as if it had a single return instead of two. The phase differences in the other two wires making their influence equivalent to that of a single return. Hence if the wires are equidistant from each other, that is, situated at the corners of an equilateral triangle, they may be regarded as three separate circuits requiring no return wires, but each affected inductively as if a return existed in the position of one of the other wires.

The wires should, when practicable, be placed nearly equidistant from each other in cases where inductive effects will be important. The nearer they are together the less the induction will be. When lights are connected to three phase circuits they must either be connected between the wires, or from each wire to a common return wire. These connections may be designated by the letter *Y* and the Greek letter Δ A reasonably good balance must be maintained at the generator on the three legs of the circuit.

22. Two Phase System.—In this system the generator armature is wound with two sets of coils which are in quadrature with each other, that is,

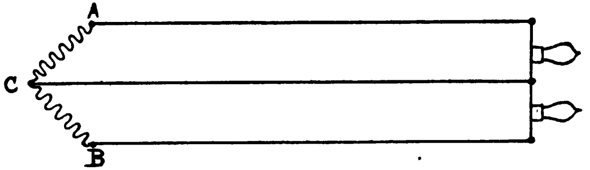


FIG. 15.

which generate E. M. F.'s which differ in phase by 90°. The motor field also has coils in quadrature and its sets of coils may be connected to the generator by two separate circuits of two wires each,

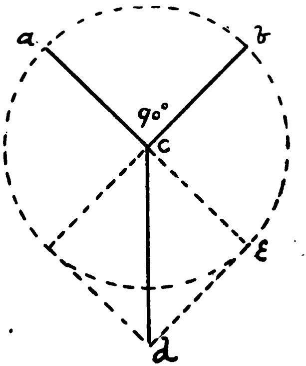


FIG. 16.

or by two wires with a common return. The two sets of coils receiving currents from the generator co-operate to cause the rotating field in the motor.

The three-wire arrangement is most commonly used. Its connections may be illustrated by Fig. 15.

If $a\ c$ and $b\ c$, Fig. 16, represent respectively the E. M. F.'s generated in the coils A C and B C, Fig. 15, both in phase and length, then $a\ b$, Fig. 16, will represent the potential difference between A and B, Fig. 15. If $a\ c$ and $b\ c$ are each 90°, $a\ b$ is equal to $\sqrt{2} = 1.414$. If in Fig. 16, $a\ c$ and $a\ b$ represent the currents in the lines from A and B, Fig. 16, then $c\ d$ will represent the current in the wire from C, hence the current in the third wire is equal to that in one of the others multiplied by $\sqrt{2}$. A comparison of these currents and E. M. F.'s will show that with the same strain on insulation, and the same energy transmitted and lost, this system requires 45 per cent. more copper than the single phase system, and about 108 per cent. more than the three phase system. If lights are run from this system the load on the two parts must be balanced. If the lights are connected between the outside wires balance will not be required, but the output of the generator will be greatly reduced since its two coils will be acting in series but in different phases.

23. *General Remarks on Distribution.*—The object of all systems of parallel distribution for lighting is to maintain at all points a potential difference suited to the lamps used, and subject to as little variation as possible. The matter of energy lost in distribution is generally of less importance than the question of maintaining constant potential,

since constant pressure makes possible the use of lamps of high economy, and thus saves energy and gives uniformity of illumination. In all systems of wiring and transmission there must be resistance of conductors and other causes which tend to create inequalities of potential. Our problem is to so arrange matters as to accomplish the following results: First, that the errors introduced are small. Second, that they tend as much as possible to equalize each other. Third, That they cannot combine to form important errors; and Fourth, that the labor necessary in adjustments is as little as possible.

In discussing systems of wiring and distribution we will use the terms defined below to designate the different parts of circuits.

Mains are the conductors to which the service connections of buildings are made.

Feeders are the conductors which connect the generating station to the system of mains.

Sub-Feeders are branchings of the feeder ends which serve to connect them to the systems of mains at two or more points instead of at a single point.

Since there can be no means of compensating for loss on mains, these must be laid out so as to give very small loss under all conditions of load, and in order that this may be accomplished with a minimum of copper, we must try to make the system of mains form a network so that if the load is particularly heavy in one place, the current will be supplied from several directions, all variations

of potential tending to equalize each other through the connecting wires.

On feeders the losses may be greater since they lead to the station where adjustments of pressure may be made to compensate for the losses. The fact that variations of feeder loss may occur also make a network of mains desirable, since such a network tends to equalize the pressure at feeder ends, and thus to throw load on the feeders having least loss.

Sub-feeders increase the number of feeding points and so reduce the distances which the current has to be carried in mains.

In the general arrangement that should be adopted in any system of mains and feeders, whether for alternating or direct currents, the feeder ends should be so situated that the general trend of current in mains is away from the station; they should also be so placed that the resistances between them are as small as possible so that they can share each other's load and equalize each other.

24. Alternating Current Wiring.—All that has been said here applies generally to direct and alternate currents. We will now discuss some of the advantages and disadvantages that belong exclusively to alternating currents. The advantages afforded by alternating currents are: First, that high potentials may be used and the drop in the lines thus reduced; and second, that methods of adjustment of pressure may be used which do not

involve loss of energy. The disadvantages of the alternating current are: First, that there is a variation in pressure in transformers at different loads which in the best transformers is very considerable; and second, that the line inductances tend to disturb distribution and to introduce uncertainty, since their effect does not depend on the current alone, but on the relative lag angles of the line and the load.

The fact that the degree of inductance of the load affects the line losses, makes the use of networks of mains more desirable with alternating than direct currents, since they will equalize the quality as well as the quantity of load on feeders.

The fact that there is a variation of pressure of from 1 to 4 per cent. in the pressure on the secondary of a transformer between full load and no load, makes it extremely undesirable that a condition should exist where transformers differently loaded are connected to the same circuit. Of course, there are some cases where it is impossible to avoid this, but in such cases the regulation cannot be good, and it will be impossible to use high economy lamps profitably on such circuits, since the pressure must be adjusted to suit the heavily loaded transformers, and consequently those which are lightly loaded subject their lamps to too high a pressure. A daily rise of 3 per cent. above normal pressure for a short time will reduce the life of an incandescent lamp of good economy one-half.

These facts and the fact that large transformers are more efficient and relatively cheaper than

small ones, make it highly desirable that secondary mains should be used as much as possible. Where secondary mains cannot be used the number of lights connected to each transformer, or set of transformers, should be as large as possible so that the variations of load will be as nearly as possible the same on all transformers. In all cases, and particularly in cases where isolated transformers or small groups have to be used, everything possible should be done to insure good distribution on the primary wiring; systems of primary mains with as many cross-connections as possible should be run, and connection to feeders made at suitable points. In connection with such a system of primary mains the advantage of running dynamos in parallel will readily be seen, since feeders connected to independent dynamos cannot connect to the same mains, and cannot equalize each other's losses.

The ideal system of alternating conductors would consist of feeders figured for small and equal loss, connected at proper points to a network of primary mains, which in turn is connected through transformers of large size suitably placed to a system of secondary mains arranged on the three-wire system. The size of mains should be so proportioned that the possible drop between transformers would be small compared with the drop in the transformers themselves, which arrangement would tend to make transformers share each other's load. Fuses should be placed in the mains between transformers and also in the prim-

ary leads of transformers, so that in case of a short circuit the section where the trouble occurred would be disconnected both from the primary and secondary systems, which would prevent the blowing of fuses on other transformers.

25. Town Lighting by Alternating Currents.—In the practical lighting of a town it is generally not possible to realize all the conditions of the ideal case just stated. This fact, however, should not lead us to lose sight of any of the principles involved; we must constantly bear in mind that we are dealing with a number of sources of error, and we must take measures to prevent their combining. In every town the bulk of the lighting is confined to one or more important streets or localities, and the proportion of it which is not within these localities is generally found in scattered, small groups rather than evenly distributed over large areas. In important lighting districts in principal streets, the methods described in the preceding pages can often be closely followed without great extra cost. In the smaller isolated groups much can be done in equalizing and controlling pressures by the use of secondary mains and large transformers. The primary wiring can also be generally so arranged as to equalize pressures between different groups of lights. Thus in most towns, systems of alternating circuits could be arranged which would give to the bulk of the lights as good, or better, regulation than is ordinarily attainable with direct currents in small areas. The cost of

installing a plant on the lines described will generally be somewhat greater than where the individual transformer system is used, but the economy of power effected and the improvement in service will always far outweigh the increase in first cost.

26. Underground Distribution.—There are many methods by which alternating currents may be distributed underground; all such work, however, may be divided into two classes, high tension and low tension. In the former only primary wires are in the street, and the transformers and their secondary circuits are in the buildings supplied. In the latter the transformers are collected in groups at convenient points, and their secondaries are connected to systems of mains which distribute the current at low tension to the points where it is used. The high tension method of distribution has been used almost exclusively for alternating currents in this country, and it possesses certain advantages, the greatest of which is low cost of installation. The low tension method generally necessitates the use of a large amount of copper in secondary circuits, but it makes possible the use of large transformers, and, in some cases, the adjustment of the number of transformers in circuit to the load on the line. The most distinct advantage, however, lies in the fact that there are no variations of pressure arising from various degrees of load on individual transformers, and it is, therefore, possible to maintain a higher regulation than is attainable on the individual transformer

system. We will first discuss some of the methods used in high tension distribution. The most common method is by lead-covered cables laid in ducts of iron or other material.

27. Ducts.—The conduits in which wires are commonly laid are of many designs, but the commonest form is a tube about 3″ in diameter. In each of these tubes from one to six cables are drawn. The ducts themselves are sometimes of iron and sometimes of other materials. The objects we should have in view in placing these conductors, are as follows:

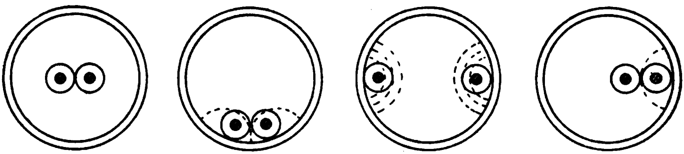
First, we should try to get the two wires of the same circuit as near together as possible, so as to reduce the passage of magnetic flux between them, whether this flux proceeds from themselves or from other wires.

Second, we should avoid round conductors whose size is such that the product of the periods per second, and the circular mils much exceeds 100,000,000, since in such wires a considerable portion of the copper is not available, as shown by Table I., page 9.

The effect of capacity in lead-covered cables may be of great importance, but since the lead covering is practically always grounded, each cable acts as a condenser and the relative positions of cables does not affect the case. A knowledge of the effects of capacity, which knowledge may be obtained by calculation, will influence our discussion as to the potential which it is desirable to use.

28. Iron Ducts.—If a single cable of an alternating circuit were led through an iron duct, an alternating magnetic field would be created in the iron walls of the tube, the lines of force encircling the wire through the iron and giving rise to great counter E. M. F. of self-induction and also to energy losses due to eddy currents in the iron.

If the outgoing and return cables are both in the same duct their effects largely neutralize each other, though the iron will still have some influence the degree of which will depend upon the relative positions of the wires.



I. II. III. IV.

FIG. 17.

Fig. 17 shows four positions which two cables might be constrained to occupy by the presence of other cables in the duct.

In case I. there will be practically no effect produced by the iron. In cases II. and III. the influence will be greater but should not increase the inductance to a very appreciable extent. In case IV. the increase of flux between the wires will be very marked and a good deal of energy may be lost in the iron. Under any given set of conditions these effects could be calculated with a fair degree of accuracy. The influence of other conductors in the

duct might increase or diminish the effects of the iron; thus their presence introduces an element of uncertainty, which is particularly undesirable. If each pair of conductors are side by side the confusion between circuits and the losses through the presence of the iron will not be great.

In ducts not made of iron the bad effects of separating the two wires of the same circuit still exist, though generally in a less degree than with iron ducts. These facts make it desirable to draw in cables in pairs which are held together in some way, or to use duplex cables.

29. Concentric Cables.—Theoretically speaking, the most desirable form of cable for alternating currents is the concentric cable in which self-induction and mutual induction with other circuits are practically nil. Where these are made for large currents, they consist of two concentric copper tubes or circular groups of small wires separated by a concentric layer of insulation and also provided with suitable outside covering. Where small currents are to be carried the inner conductor may be made solid. The mechanical properties of concentric cables are such as to make their insulation difficult and to make their use undesirable in many cases.

30. Low Tension Distribution.—A study of the peculiarities of the incandescent lamp will show that very small variations of potential on distributing mains are an important source of loss to electric light companies since they are sure to entail

an irregular service to customers and a small amount of light delivered in proportion to the energy expended. This matter of regulation of potential seems to have received less careful attention in this country than in Europe, although in some of our large direct current stations excellent results are obtained. The reason for our backwardness in this matter is probably to be found in the fact that most of our towns are much scattered and that we have naturally fallen into the use of methods that will give fair results in towns of this class without excessive cost.

In alternating distribution the losses in transformers are a source of error which do not exist with direct currents, and the magnitude of the variations in the secondary potential of transformers with change of load are such as to make good regulation impossible unless these variations can be equalized or compensated for. Where customers are connected to individual transformers this equalization or compensation is impossible since the station potential must be adjusted to suit the mass of the load, and is consequently wrong for individual transformers on which the average condition of load does not exist.

Systems of secondary mains fed by large transformers or groups of transformers suitably placed afford a means avoiding the variations of pressure arising from this cause. The condition of load on the group of transformers may be compensated for by adjustment of primary pressure, or the number of transformers in circuit may be varied to suit the

load so that the transformers are always working at good efficiency, and so that variations through change of load are small. In direct current distribution the principal sources of error are the losses in feeders which are necessarily large on account of the cost of copper. With alternating currents these feeder losses can be made very small and the function of the secondary mains is to equalize the losses in transformers. These losses or variations are so much smaller than those introduced by direct current feeders, that the possibilities of regulation with alternating currents are much better than with the ordinary methods of direct current distribution. In America we are accustomed to seeing good regulation only in direct current plants, while in Europe, where this matter of secondary distribution has been developed thoroughly, both with alternating and direct currents, it seems to be conceded that the direct current work can compare favorably with the alternating in the matter of distribution only when storage batteries are used in sub-stations whose functions in many ways correspond to those of the transformer sub-station or group.

The use of the same alternating circuits for light and power, which is now coming into vogue, increases the desirability of systems of secondary mains since it is advantageous to equalize the character of load on all wires, so that one branch of a circuit will not be highly inductive while the others are non-inductive, since in that case the line losses will affect the branches of the circuit differently.

Where current is distributed on secondary mains, it is of course necessary to use a low potential since incandescent lamps for more than 120 volts are not much used. This necessitates the use of large conductors, although the potential effective for distribution may be increased by the use of the three wire system. With large conductors the inductance will be great in proportion to the resistance, unless the conductors are so placed with relation to each other that the inductance is minimized. In very large circular conductors all the copper will not be available for conductivity, as has al-

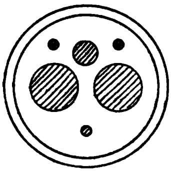


FIG. 18.

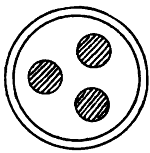


FIG. 19.

ready been explained. These considerations and others make it desirable that a low frequency should be used on such circuits, while the use of arc lights with incandescent circuits makes a frequency much less than 60 ~ undesirable. Since at this frequency we can use conductors one inch in diameter with a loss of only 13 per cent. in conductivity, we see that the surface effect is not an important consideration. By using flat conductors instead of round, and placing them close together in the same tube, induction and surface effect can both be practically eliminated. By properly shap-

ing and placing the conductors, coppers of one square inch and over can be used at 60 cycles practically without greater losses than would be experienced with continuous currents. Figs. 18 and 19 show sections of three-wire feeders and mains now commonly used for direct current distribution. Figs. 20 and 21 show sections which might conveniently be used, and which would make induction negligible with conductors of 1,000,000 circular mils, except in cases of highly inductive load.

Very large feeders are not necessary with alter-

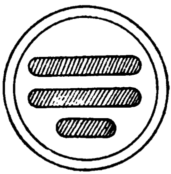


FIG. 20.

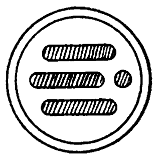


FIG. 21.

nating currents since the systems of mains can be fed at as many points as desired from groups of transformers. A pair of conductors in an iron pipe like Fig. 18, each copper having a cross section of one square inch, would, at a pressure of 2,000 volts, transmit three miles the necessary current to operate 10,000 incandescent lamps with a drop of about 7 per cent. in line and transformers.

A system of underground mains fed by groups of transformers, each group connected to a feeder with very small drop, should, if properly designed, give a better regulation of pressure than is possible

with the direct current methods generally used in this country. The load on transformers can be equalized and the losses on feeders adjusted by the use of inductive resistances, or by other means which practically waste no power and make the use of more than one generator potential unnecessary. Pressures on the mains can be shown in the station by means of pressure wires and high resistance indicators, and any desired degree of accuracy of adjustment can be made. The recent developments, which have made practical the use of good alternating motors with lighting circuits, are sure to lead to the wider use of secondary mains for alternating currents. The explanations of capacity effects in the following sections will show that it may sometimes be undesirable to use very high potentials for underground distribution. The actual cost of copper is, however, not the most expensive part of an underground system, and in most cities little could be gained by using more than 2,000 volts, which is a convenient generator potential.

31. Effects of Capacity.—When a condenser or other system having electrical capacity, is subjected to an alternating E. M. F., a current will pass through it equal to $e \times 2\pi n \times K$ where $e =$ the E. M. F., $n =$ the $\sim$ per second, and $K =$ the capacity in farads, or millions of microfarads. Hence, if we have a line with a capacity between wires of 1 microfarad, that is, $\frac{1}{1000000}$ farad with an electromotive force of 10,000 volts and a fre-

quency of 60 ~ per second, the condenser current will be

$$\frac{1}{1,000,000} \times 10,000 \times 60 \times 2\pi = 3.76 \text{ amperes.}$$

Thus a condenser may be said to have a resistance or impedance of

$$\frac{1}{2\pi n K}.$$

Since we have used the terms energy resistance and inductive resistance to designate the energy

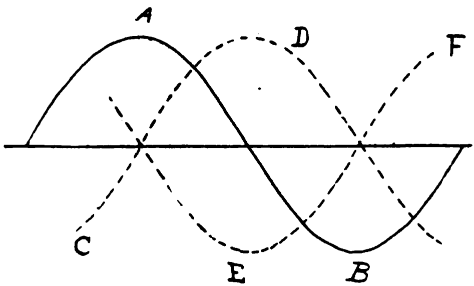


FIG. 22.

and inductive component of the impedance, we will use the term capacity resistance to designate this quantity.

As has been explained, this quantity, like the inductive resistance, is in quadrature with the current, but differs in phase from the inductive resistance by 180°, having its maximum positive value when the inductive resistance has its maximum negative value. In Fig. 22, if the curve A B repesented the current, the curve D C might represent the

inductive resistance, and the curve E F the capacity resistance. If these two quantities are equal, as the curves in this figure indicate, they will neutralize each other.

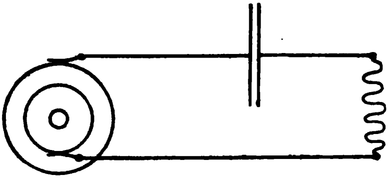


FIG. 23.

If we have a circuit having energy resistance and inductive resistance and in it insert a condenser having a certain capacity resistance as shown in Fig. 23, the total impedance is illustrated by Fig. 24.

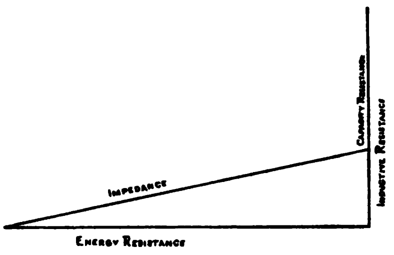


FIG. 24.

If the circuit has no inductive resistance it will be illustrated by a triangle like Fig. 25.

If the inductive resistance is less than the capacity resistance it may be illustrated by a triangle like Fig. 26.

Thus the effect of capacity on a circuit depends upon the amount and position of the inductances in the circuit.

Line capacity acts like a condenser connected between the wires at the middle point of the line as

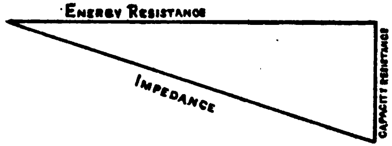


FIG. 25.

shown in Fig. 27. If we know the capacity we know the condenser resistance. This condenser resistance is in parallel with the impedance of the portion of the circuit beyond C R and the resultant of these two impedances in parallel, is the impedance between the points C & R; this is the reciprocal of the resultant of the reciprocals of the two impedances in question. The resultant impedance of a capacity and an impedance in parallel can be found in the manner described in Sec. 8.

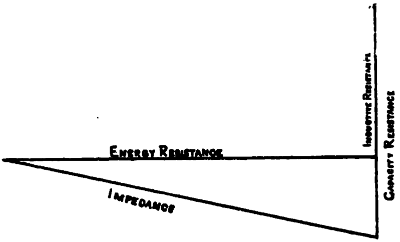


FIG 26.

32. Graphic Representation.—To illustrate some of the practical effects of capacity on distribution we will construct diagrams representing possible cases. Fig. 28 represents a circuit where 256 K. W. is transmitted through step-up transformers, and a line having five per cent. copper resistance and three per cent. inductive loss to a load having an energy factor of .99. The line having a capacity between conductors of 5.3 microfarads. Such a case might exist in a pair of long cables containing large conductors. The maximum potential on the line

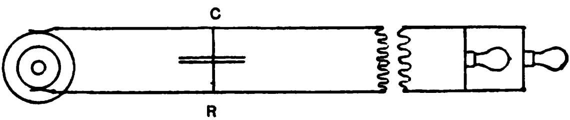


FIG 27.

is 4,000 volts. We construct the diagram on the scale of 1″ = 800 volts. A B represents the step-up transformers having one per cent. resistance and six per cent. inductive loss. B D represents the line with a resistance drop of 200 volts. D E represents the load with its proper lag angle, as its impressed E. M. F. would be if there were no capacity in the line. The impedance of this circuit is its $\frac{\text{impressed E. M. F.}}{\text{current}} = \frac{4{,}000}{64} = 62.5$ ohms. In parallel with this load circuit we have a condenser resistance of $\frac{1}{2\pi n c}$ ohms; this, at 60 cycles per second,

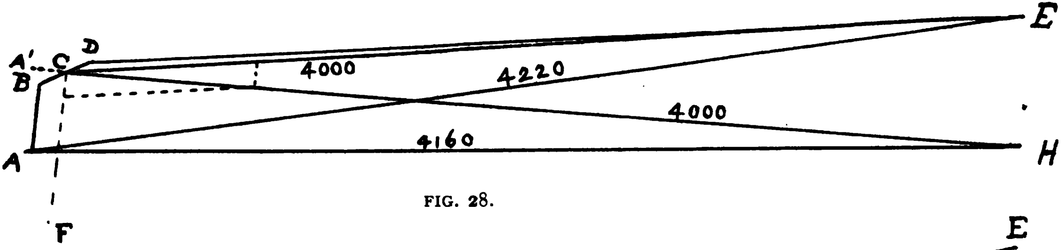


FIG. 28.

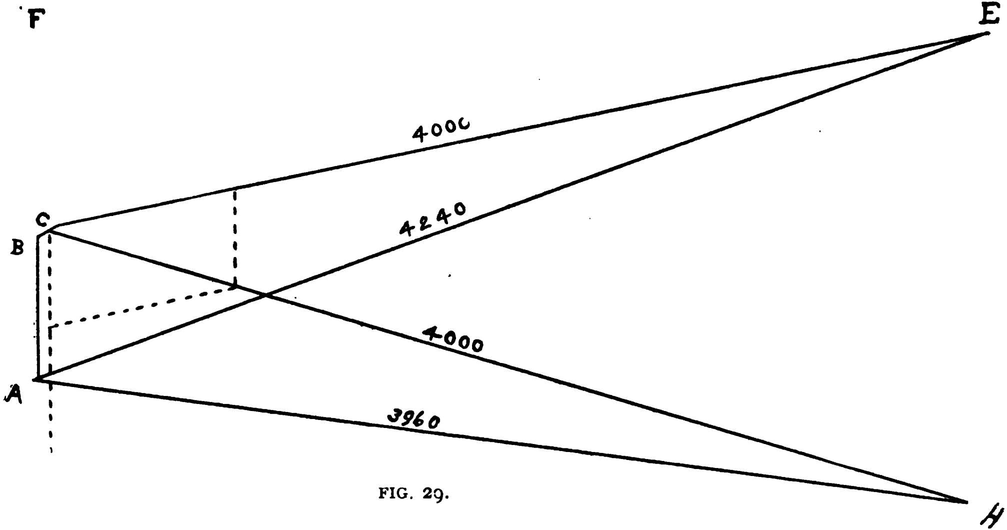


FIG. 29.

$= \frac{1}{6.283 \times 60 \times 5.3} \times 1{,}000{,}000 = 500$ ohms (the 1,000,000 reduces the microfarads to farads). The phase of the E. M. F. impressed at the point C will be that of the impedance which is the resultant of this capacity resistance, and the impedance of the load circuit in parallel. The phase of the capacity resistance is shown by the vertical line C F in quadrature with the current. If we construct a parallelogram on the angle E C F, whose sides are in the proportion of $\frac{1}{500}$ to $\frac{1}{62.5}$ the diagonal from C will give the phase of the resultant impressed E. M. F. When one generator is so adjusted that this pressure is 4,000, the E. M. F. required will be represented by C H. The E. M. F. at the generator terminals will then be represented by A H = 4,160 volts. If the line had no capacity, the pressure at the generator terminals would have to be A E = 4,220 volts. From an examination of this figure we see that the combined effect of the capacity and the inductance of the transformers is to raise the potential on the line above what it would otherwise be, or apparently to increase the ratio of transformation. To really show the generator E. M. F. for which the dynamo must be excited and compounded, we should add at A a triangle, showing the resistance and inductive resistance of the generator armature, the lines A H and A E representing pressures at the dynamo terminals. If there were no inductance between the centre of the line and the generator,

that portion of the circuit might be represented by the line C A′, and since A′ E is a little shorter than A′ H we see that the requisite generator pressure would be slightly raised instead of being lowered by the presence of the capacity.

Fig. 29 represents about the conditions that might exist in the same circuit at ¼ load. The inductive loss of the step-up transformers would then be increased to at least 15 per cent., while their resistance loss would be practically nil; the line losses would also be very small. The load would be more inductive, as shown by the raising of the point E. The impedance of the load would be four times what it formerly was, and will now be ½ the capacity resistance. Hence the parallelogram which we construct to find the phase of the resultant impedance has sides in the proportion of 2 to 1, and C H represents the resultant impressed E. M. F. This being 4,000 volts, the pressure required, the E. M. F. at generator terminals is A H = 3,960, while that required, if there were no capacity, would be 4,240. Thus the line capacity reduces the required generator pressure by 4 per cent. at ¼ load, and by 1 per cent. at full load, the condenser current being 12.5 per cent. of the full load current.

If the step-up transformers were not used the generator terminal pressures would be found by measurements from the point B in both figures, and it is apparent that the capacity would have practically little effect on distribution unless the armature circuit of the generator was highly in-

ductive. The following record of an actual test made on a piece of cable shows an extreme case of the application of the principles illustrated by Figs. 28 and 29. A piece of cable, 240 feet long, having a capacity of .016 microfarad was connected to a small transformer secondary, which gave normally on open circuit 3,000 volts; one end of the cable was connected to one secondary terminal, and the other terminal was connected to the lead covering. The volts at the terminals then measured 10,000. This case might be illustrated by a figure similar to those given. The distance corresponding to A H, Fig. 29, would be only three-tenths of that corresponding to A B. If no energy were consumed in the insulation of the cable the line B H would be vertical. Any energy consumed in the cable in leakage or insulation hysteresis would tend to make the line B H trend to the right.

The reader will observe that the effects of line capacity will be generally much more marked where step-up transformers are used.

If we are considering the degree of compounding that a generator will require to make it self-regulating when connected directly to a line having capacity, the self-induction of the armature may be an important factor, since it will act in the same way with the capacity, as we have shown in the case of the inductance of transformers. The E. M. F. at its terminals may be greater than the generated E. M. F., for which the field must be excited. Since the bad effects of capacity come at times of very light load, the inductance of the

generator will generally be unimportant unless it happens that so small a generator is run at such times that the losses in its armature are considerable. The generator armature forms part of the circuit, and, strictly speaking, its impedance should always be considered as one component of the total impedance of the circuit.

TABLE IV.

CAPACITY OF LEAD-COVERED CABLES. INSULATION 0.15″ THICK.

Gauge No. B. & S.	Capacity in Microfarads per Mile.		
	Gutta percha.	India rubber.	Jute.
0000	.68	.60	.65
0	.52	.46	.50
3	.41	.36	.39
6	.32	.28	.31
9	.26	.23	.25

The above Table IV. gives capacities per mile between the conductor and the covering. Where both outgoing and return cables are grounded, or in contact, as when laid in ducts, the capacity between conductors per mile of conductor is ½ the figure given in the table.

As has been explained, the effect of line capacities are practically the same as would be produced by equivalent condensers placed between the wires at the middle point of the line.

Except in very exceptional cases the capacities of aerial lines are so small as to be entirely negligible. Table V. gives the capacities of various sizes of conductors strung at distances of 12, 18 and 24 inches apart.

TABLE V.

CAPACITIES OF LINES IN MICROFARADS PER MILE OF CONDUCTOR.

Gauge B. & S. Wire.	Distances Between Centres of Wires.		
	12 Inches.	18 Inches.	24 Inches.
0000	.0226	.0204	.0192
000	.0220	.0200	.0188
00	.0214	.0194	.0184
0	.0208	.0190	.0180
1	.0202	.0186	.0176
2	.0169	.0180	.0172
3	.0192	.0176	.0168
4	.0188	.0172	.0164
5	.0182	.0168	.0160
6	.0178	.0166	.0158
7	.0174	.0162	.0154
8	.0170	.0160	.0152
9	.0168	.0158	.0148
10	.0164	.0152	.0146

33. *Conclusion.*—A first consideration of the various phenomena that may influence distribution by alternating currents, tends to impress one with the idea that the difficulties to be met, must constitute

serious objections to the use of currents of this class. A more thorough study of the principles involved shows us that these peculiarities are not of great importance where good apparatus and proper methods are used. Such a study also shows us, that in cases where these principles are not considered in laying out work, the results obtained may be vastly different from those expected.

We have seen that in circuits whose power factors are large, the effects of inductance in lines and transformers may be almost negligible, while with inductive circuits, the variations of pressure caused by these inductances may be of great importance. Thus, the more inductive resistance we put into a circuit, the greater the effect of each unit of inductive resistance. To avoid inductance in circuits, attention must be given to the following points:

The transformers should be large and of good design, and should be operated as nearly at full load as possible. We should not introduce large losses through lines having much inductance, such as wires of large size on poles. We should not use too much motor load with lighting circuits, unless suitable arrangements for adjusting and equalizing pressures can be made.

All transformers have inductance, which affects their regulation more or less, according to the degree of inductivity of their load; hence it is undesirable to have two transformers on the same circuit, one operating on a non-inductive and the other on an inductive load; that is, if it is desired to operate incandescent lamps from both.

Since we can use high potentials in feeders, we do not have large losses of potential to deal with in using alternating currents. As we have seen, however, there are several sources from which irregularities arise. If these errors can combine, they will be serious, whereas, if they can be equalized and made to balance, their effects may be very slight. Thus, the true means of obtaining good results in alternating current distribution is by the use, to as large an extent as possible, of systems of secondary mains.

[THE END.]